Georgia Tech Laboratory for Smart Structural Systems

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Battery-Free Antenna Sensors for Strain and Crack Monitoring of Bridge Structures

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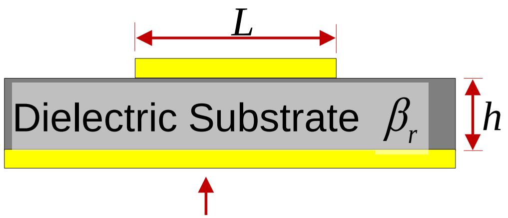
Outline

- Research Background & Motivation
- Thermal Stability Tests
  - Temperature Chamber Test
  - Day-long Outdoor Test
- Material Property Tests
  - Constitutive Relationship of Substrate
  - Constitutive Relationship of Glue
  - Dielectric Constant of Substrate
- Multi-Physics Simulation
- Validation Tests
  - Strain Sensing Test
  - Crack Sensing Test
- Conclusion

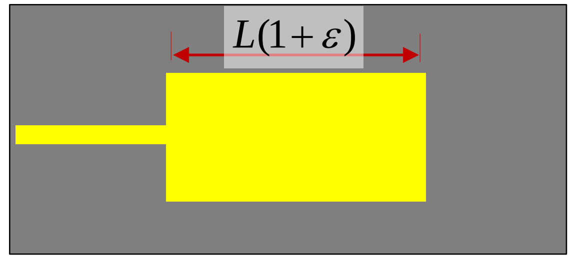
Strain Sensing Mechanism

Patch Antenna

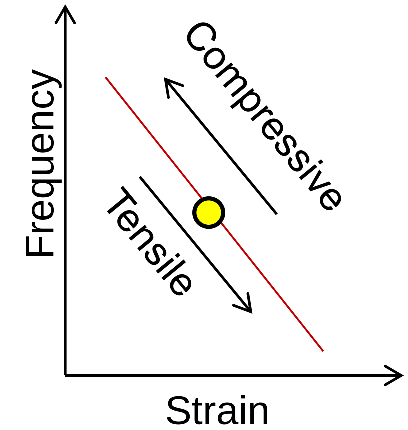


Metallic ground plane

Side View



Top View



Electromagnetic resonance frequency of a patch antenna (at zero strain):

$$f_{\mathrm{R0}} \approx \frac{c}{2L\sqrt{\beta_{\mathrm{r}}}}$$

c -- speed of light

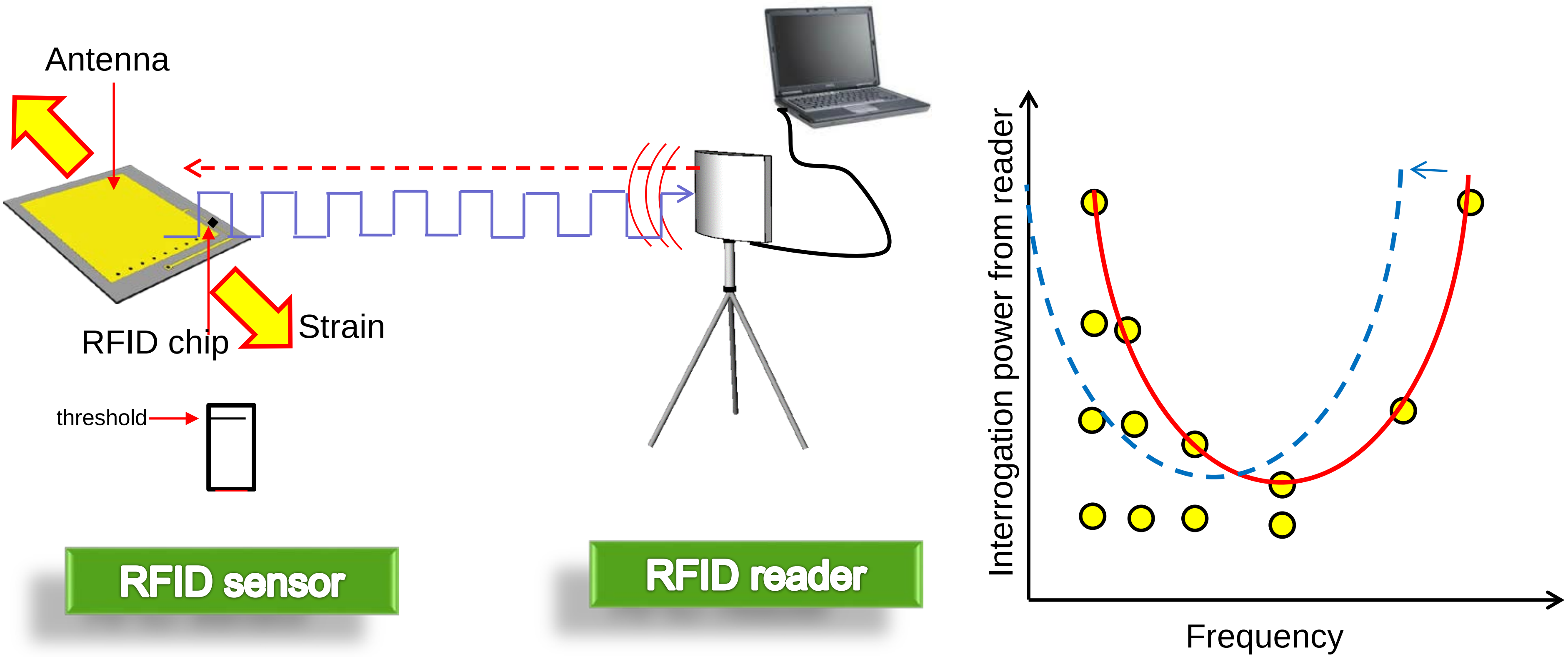
L -- length of microstrip patch antenna (half wavelength)

β_{r} -- effective dielectric constant of the antenna substrate

Under strain ε, resonance frequency shifts to $f_{\mathrm{R}} \approx \frac{c}{2(1+\varepsilon)L\sqrt{\beta_{\mathrm{r}}}} = \frac{f_{\mathrm{R0}}}{1+\varepsilon} \approx f_{\mathrm{R0}}(1-\varepsilon)$

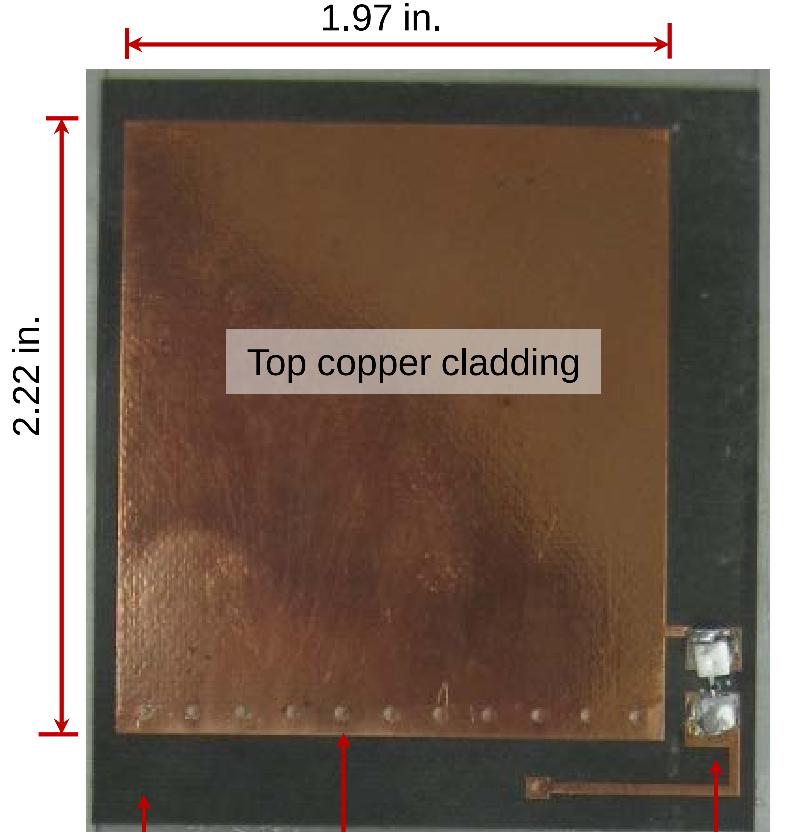
Strain sensitivity is $S = \frac{f_{\mathrm{R}} - f_{\mathrm{R0}}}{\varepsilon}$ (Hz/με)

RFID Reader-Sensor System

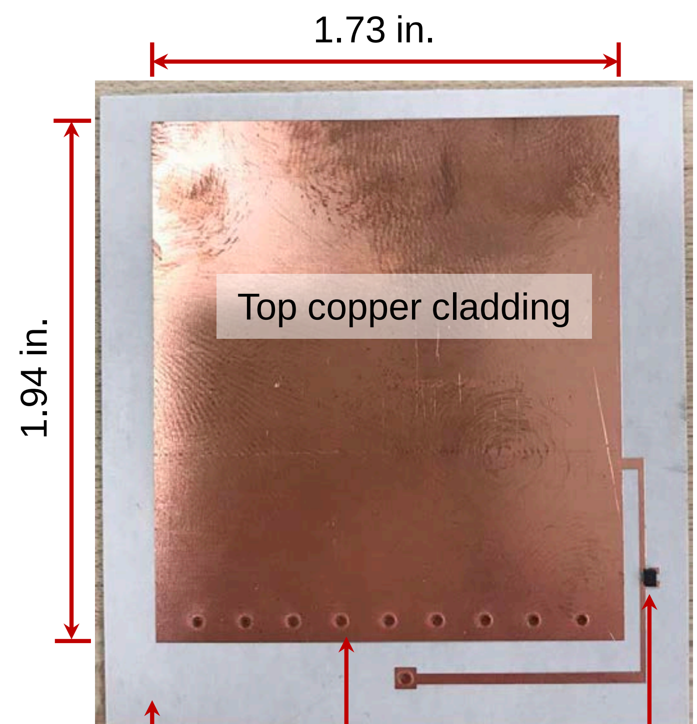


Antenna Sensor Design

Previous Design



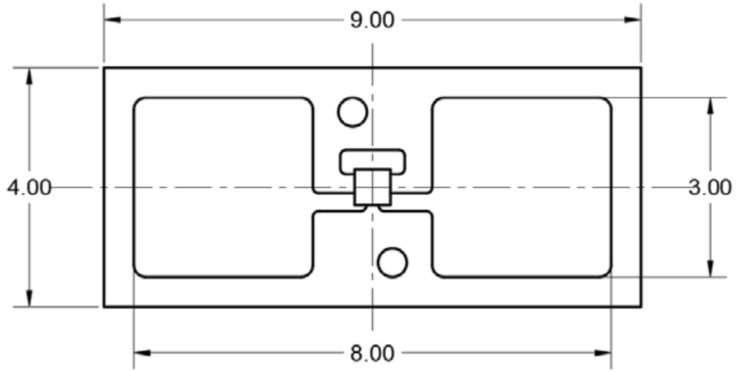
New Design



Difference from Previous Design

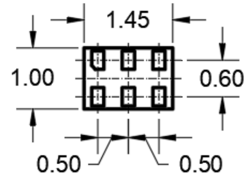
- **Chip**

Old chip: SL3S1002 (Unit: mm)



Impedance: 13.3-j122 Ω

New chip: SL3S1013 (Unit: mm)

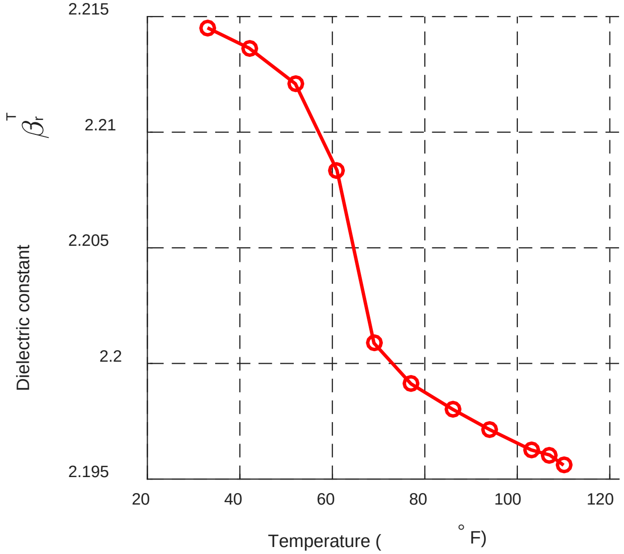


Impedance: 21.2-j199.7 Ω

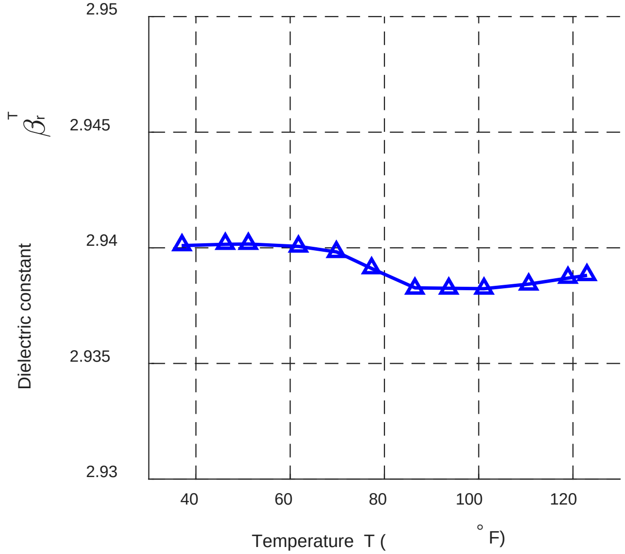
- **Substrate dielectric constant β_r**

$$f_{R0} \approx \frac{c}{2L\sqrt{\beta_r}}$$

RT/duroid® 5880



RT/duroid® 6202



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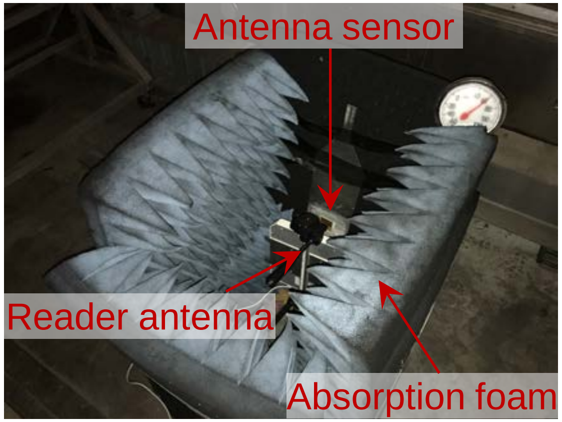
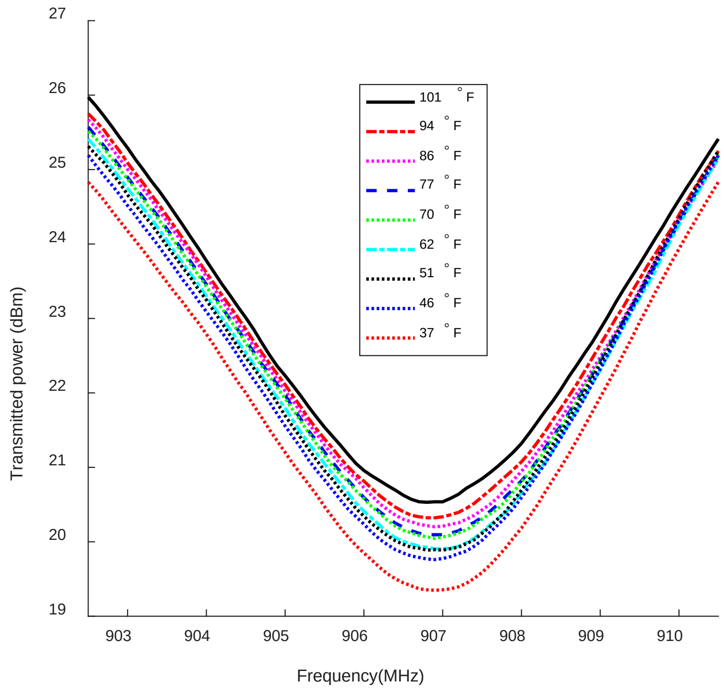
Temperature Chamber Test

- Thermal influence on the new substrate material RT/duroid® 6202 is investigated through a temperature chamber experiment.
- At each temperature step, sweep frequency band 902.5 ~ 910.5 MHz.
- From transmitted power curve, resonance frequency is extracted.
- RT/duroid® 6202 is thermally stable on dielectric constant.

Experiment setup

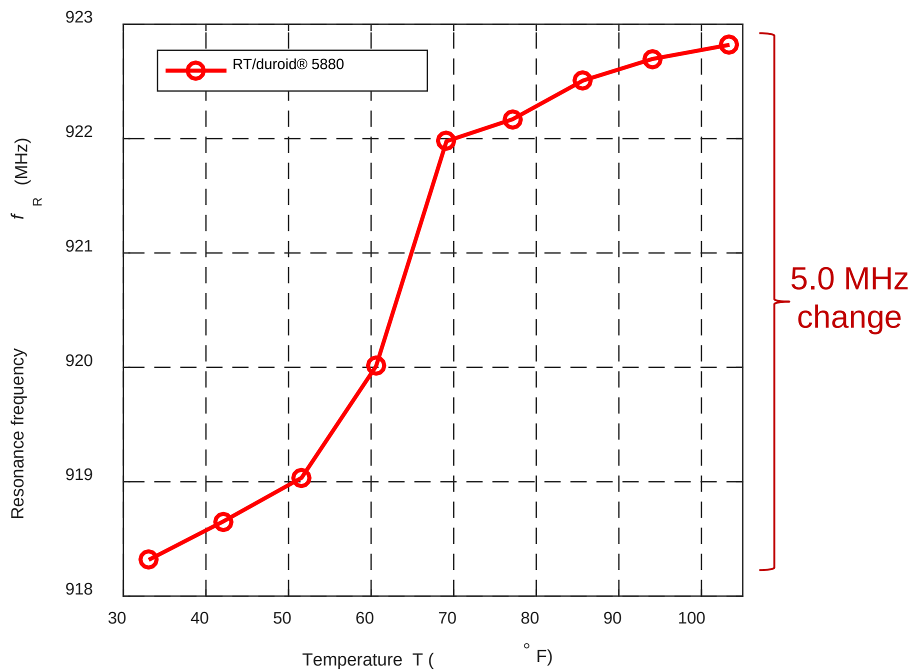


Transmitted power

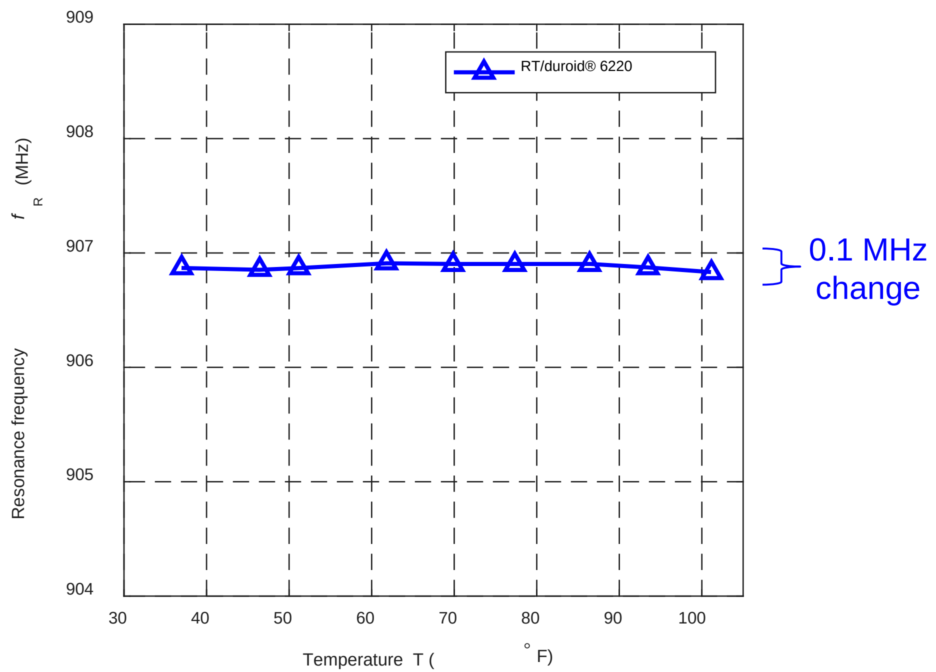


Comparison with RT/duroid® 5880

RT/duroid® 5880



RT/duroid® 6202



Dielectric constant changes significantly due to temperature fluctuation.

Dielectric constant is more stable to temperature fluctuation.

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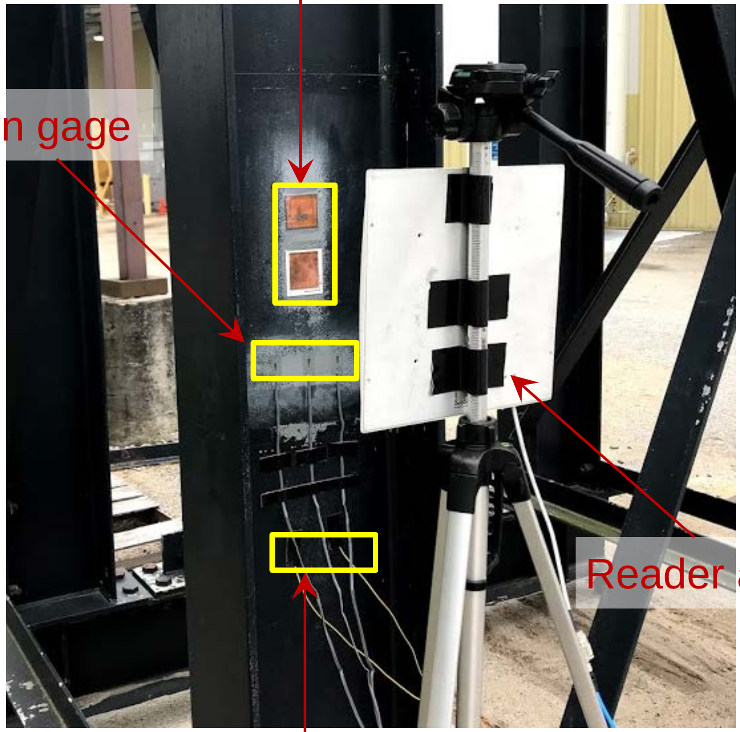
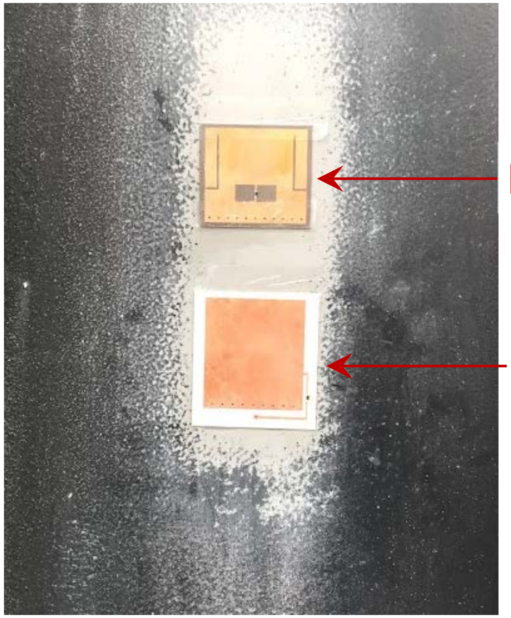
Outdoor Test

Experiment setup

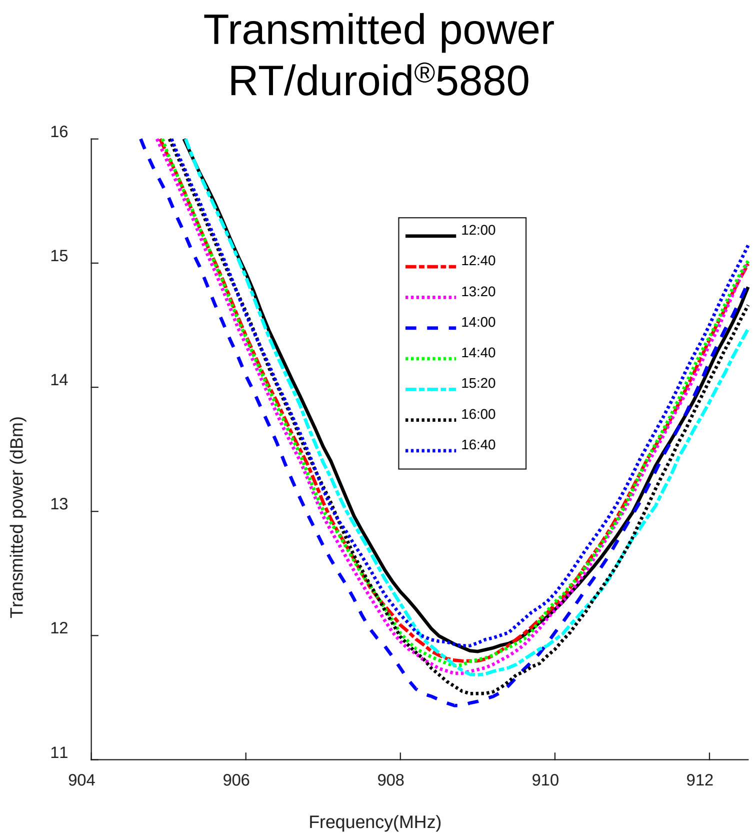


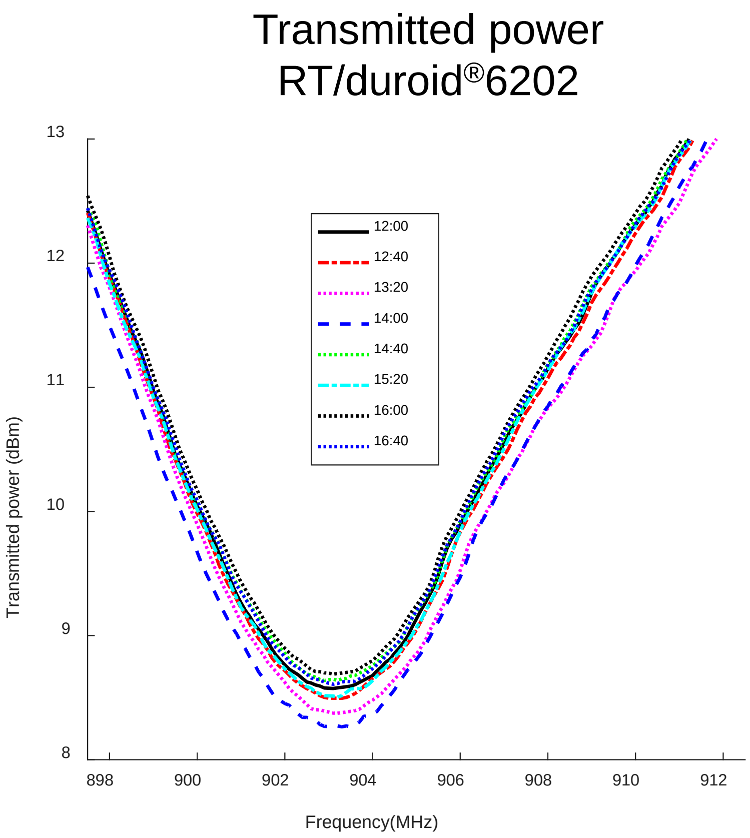
Antenna sensors



Outdoor Test Results

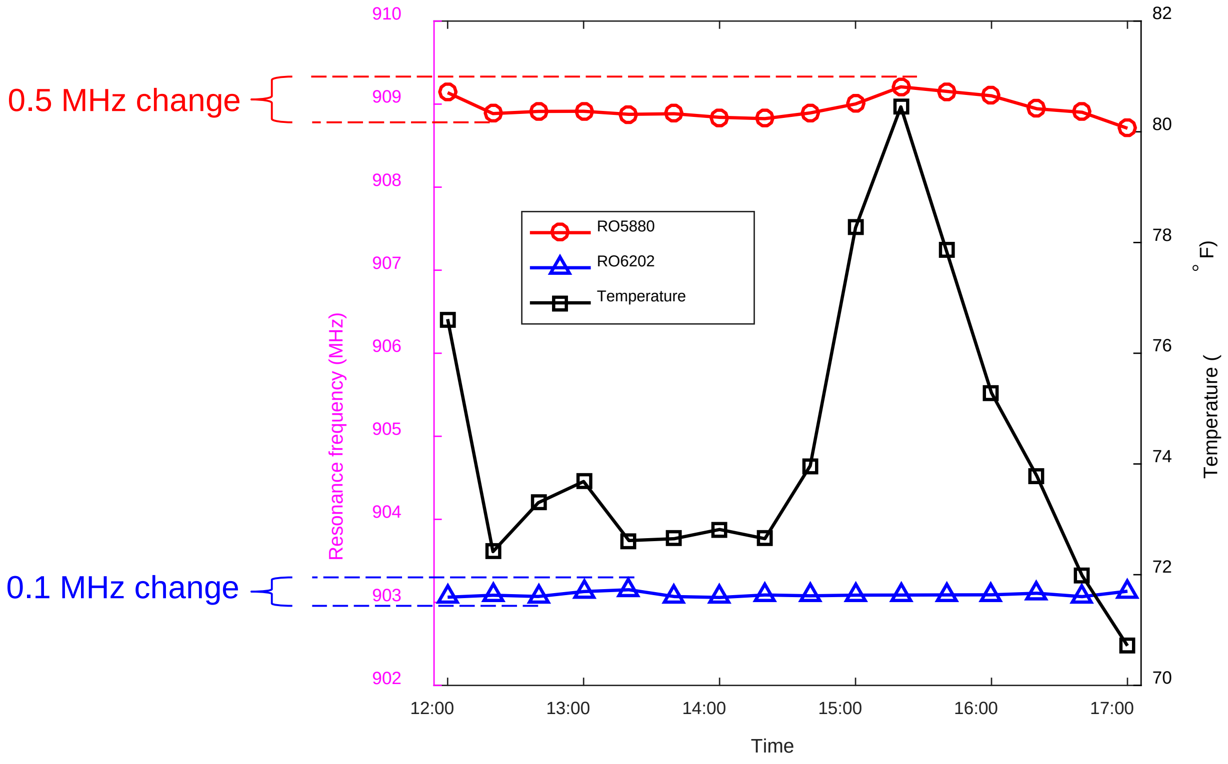
At each time step, sweep frequency band 897.5 ~ 912.5 MHz





Comparison with RT/duroid® 5880

- Comparing with RT/duroid®5880, RT/duroid® 6202 is more stable under outdoor environment disturbance, including temperature variations.



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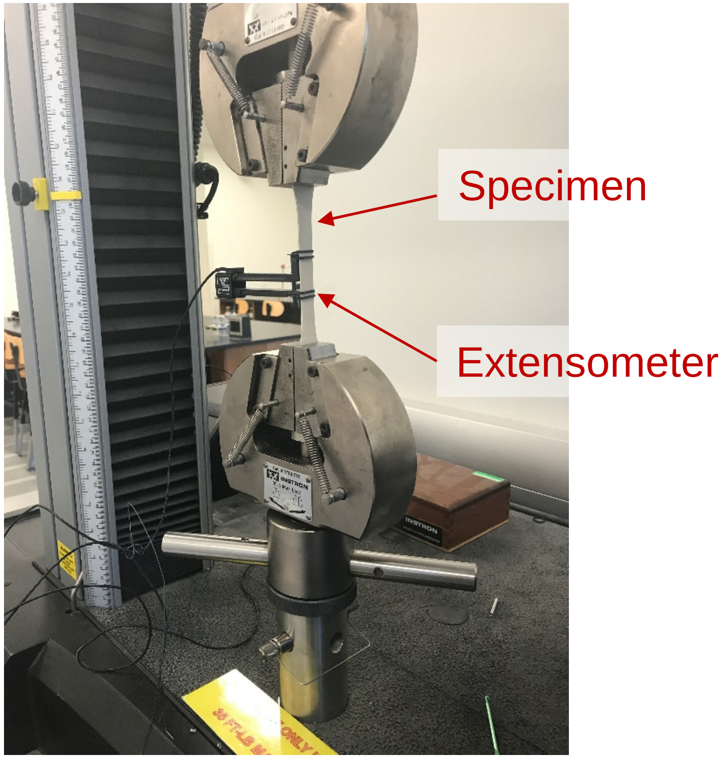
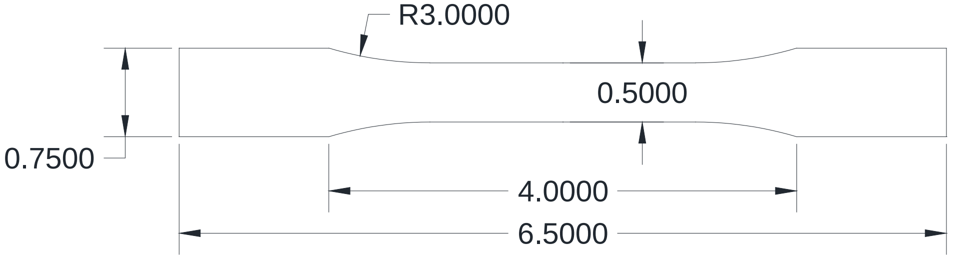
Mechanical Property Test

Experiment setup

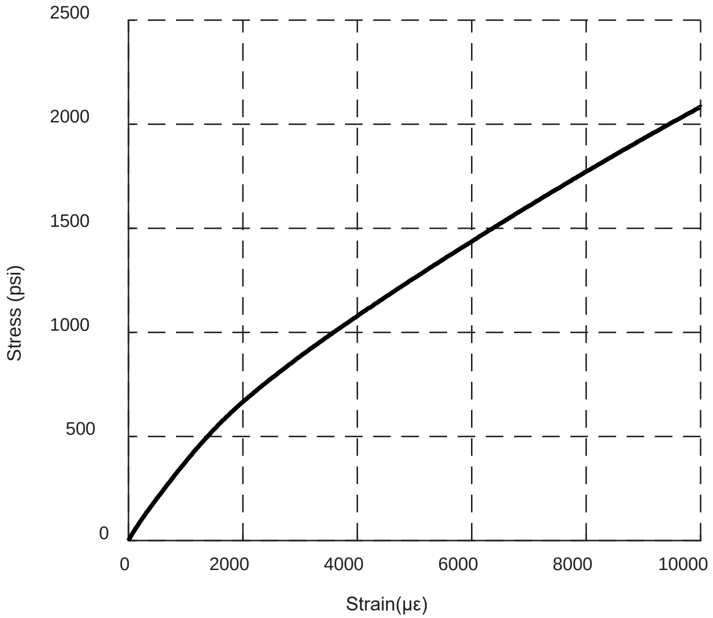


Specimen dimension



Unit: in

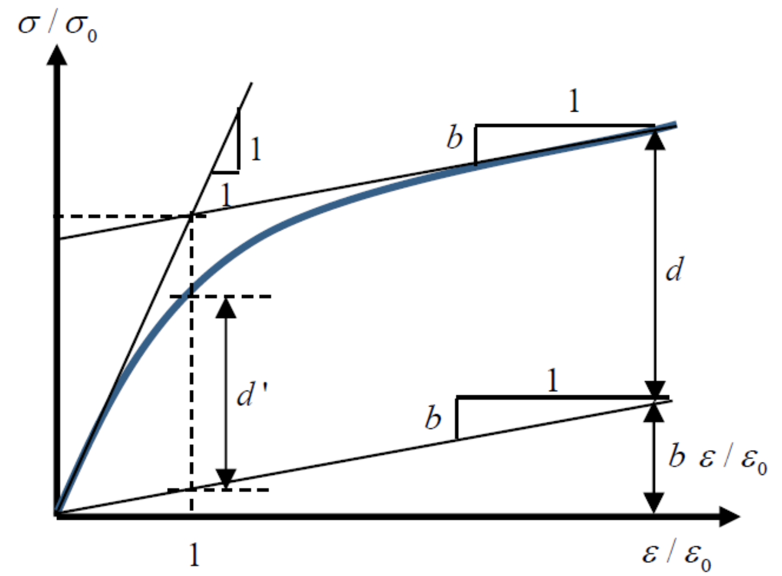
Strain-stress relationship



Menegotto-Pinto Model

Menegotto-Pinto model

$$\frac{\sigma(\varepsilon)}{\sigma_0} = b\,\frac{\varepsilon}{\varepsilon_0} + \frac{(1-b)\,\frac{\varepsilon}{\varepsilon_0}}{\left[1+\left(\frac{\varepsilon}{\varepsilon_0}\right)^n\right]^{\frac{1}{n}}}$$



Update parameters: $b, n, \sigma_0, \varepsilon_0$

b : Final tangent stiffness

n : Nonlinear factor

ε_0 : Normalized strain

σ_0 : Normalized stress

Updated Property Along Longitudinal Direction

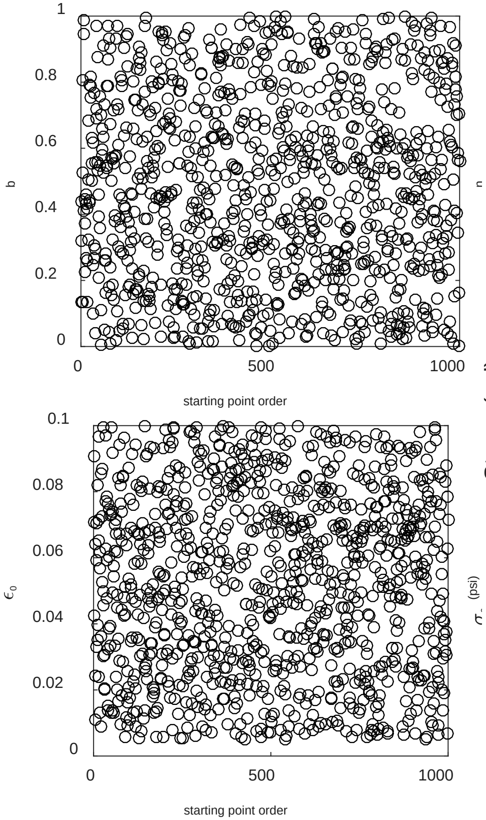
$$\mathbf{x}_0 = [b, n, \varepsilon_0, \sigma_0] = [0.5, 2.5, 0.05, 5500] \text{ (one example)}$$

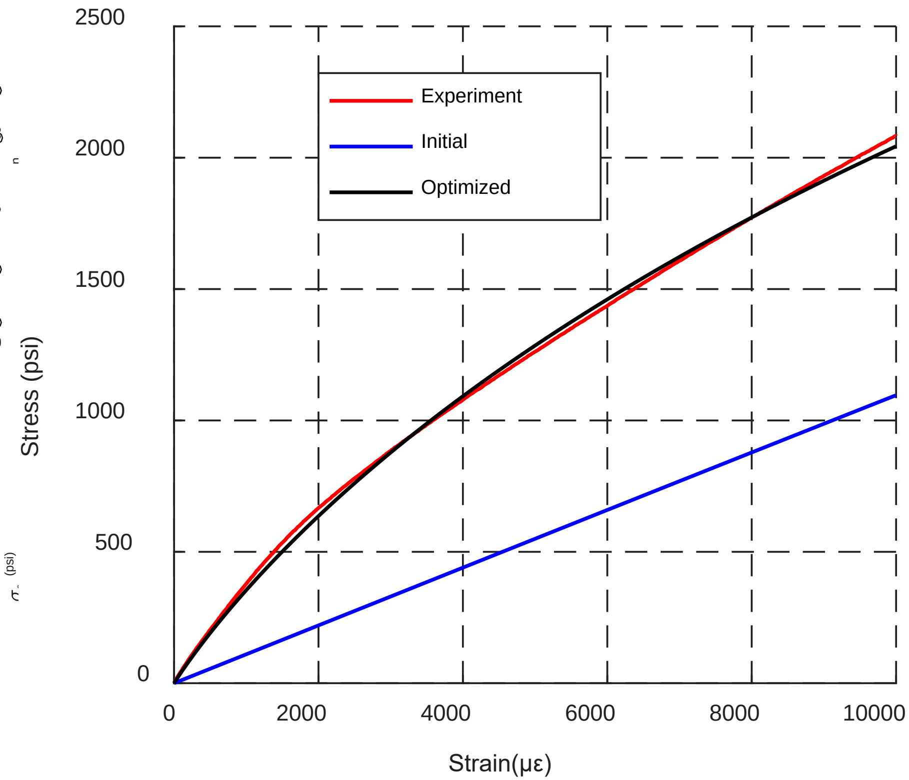
$$\mathbf{x}_\mathbf{L} = [b, n, \varepsilon_0, \sigma_0] = [0, 0.0001, 0.005, 1000] \qquad \mathbf{x}_\mathbf{U} = [b, n, \varepsilon_0, \sigma_0] = [1, 5, 0.1, 10000]$$

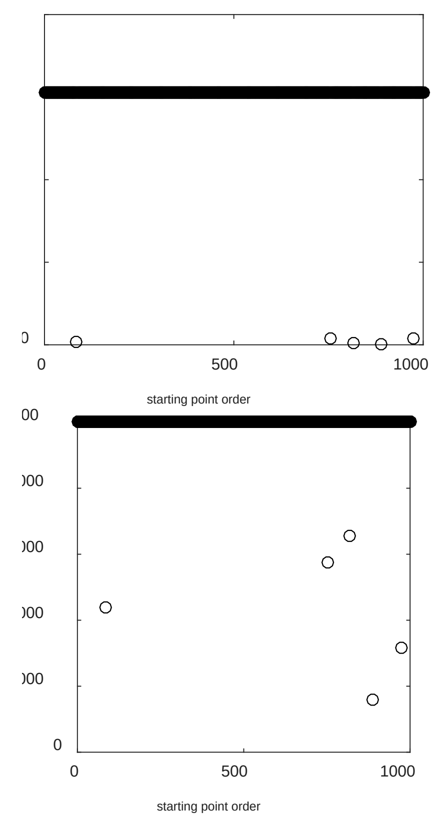
$$\mathbf{x}^* = [b, n, \varepsilon_0, \sigma_0] = [2 \times 10^{-14}, 0.61, 0.02, 10000]$$

Starting points (1000) are generated

Optimized parameters







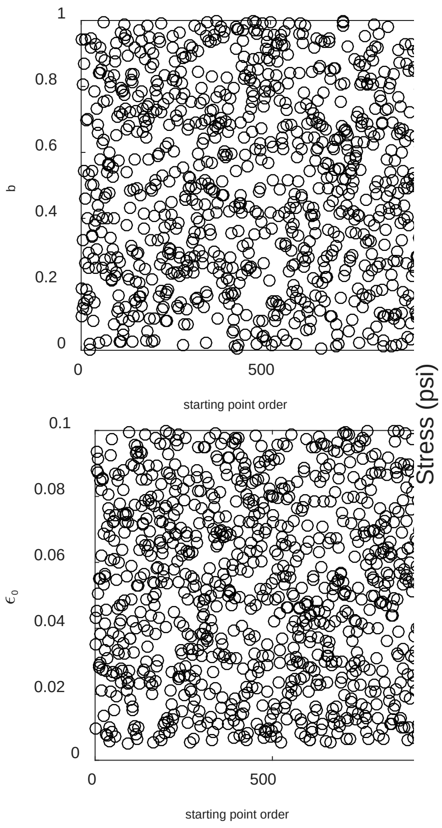
Updated Property Along Transverse Direction

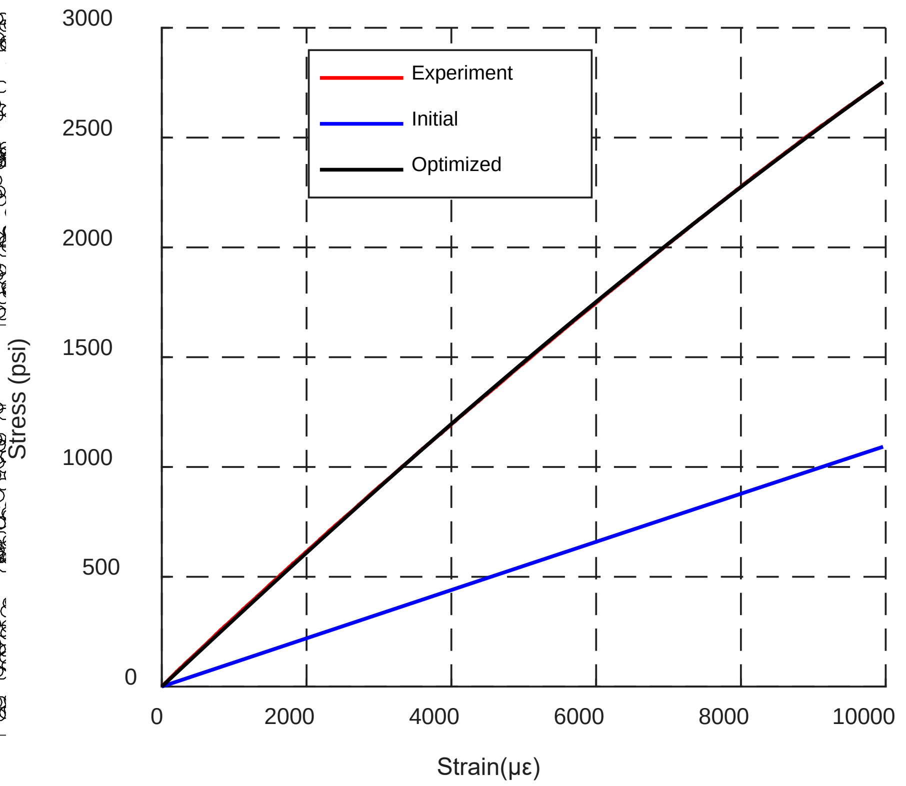
$\mathbf{x}_0 = [b, n, \varepsilon_0, \sigma_0] = [0.5, 2.5, 0.05, 5500]$ (one example)

$\mathbf{x}_\mathbf{L} = [b, n, \varepsilon_0, \sigma_0] = [0, 0.0001, 0.005, 1000]$ $\quad \mathbf{x}_\mathbf{U} = [b, n, \varepsilon_0, \sigma_0] = [1, 5, 0.1, 10000]$

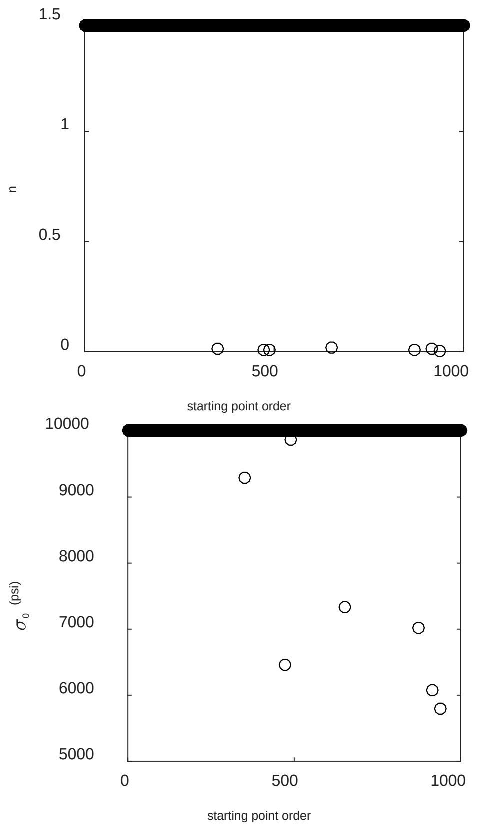
$\mathbf{x}^* = [b, n, \varepsilon_0, \sigma_0] = [2 \times 10^{-14}, 1.48, 0.03, 10000]$

Starting points (1000) are generated





Optimized parameters



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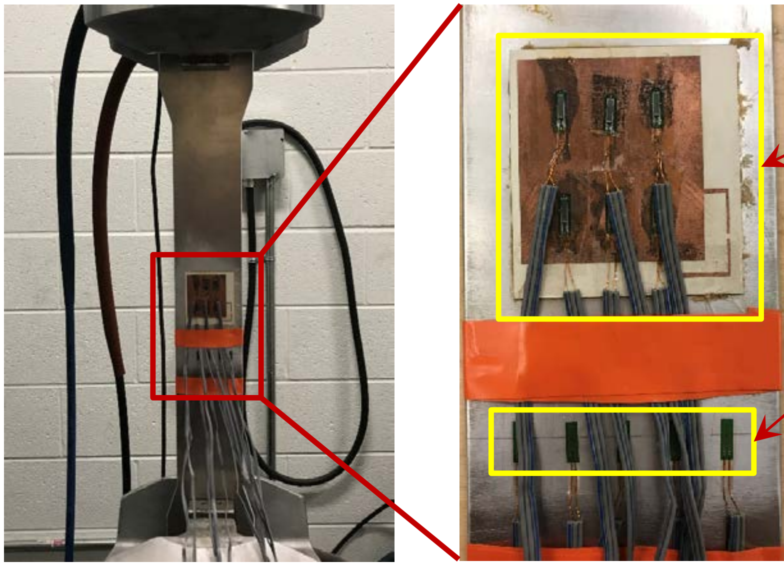
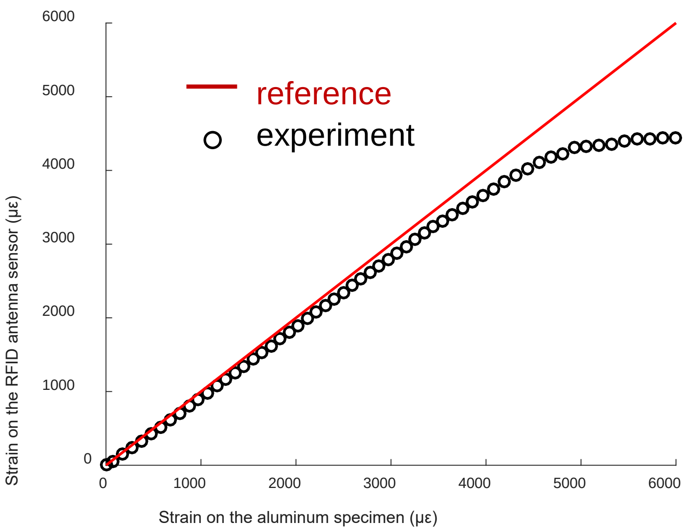
Strain Transfer Ratio Test

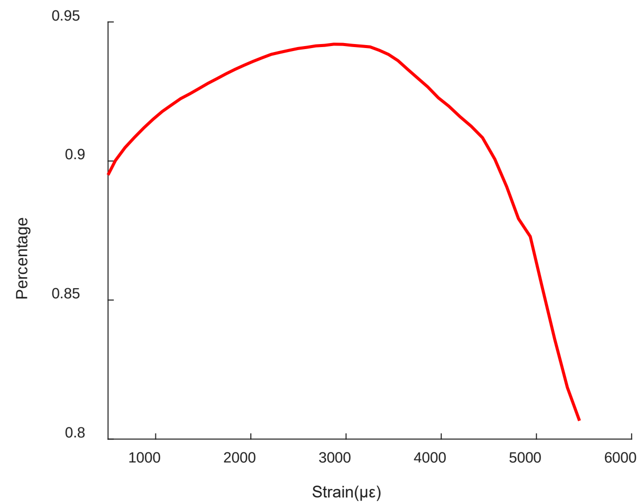


Six strain gages (#1 ~ #6) are installed on top of an RFID patch antenna sensor.

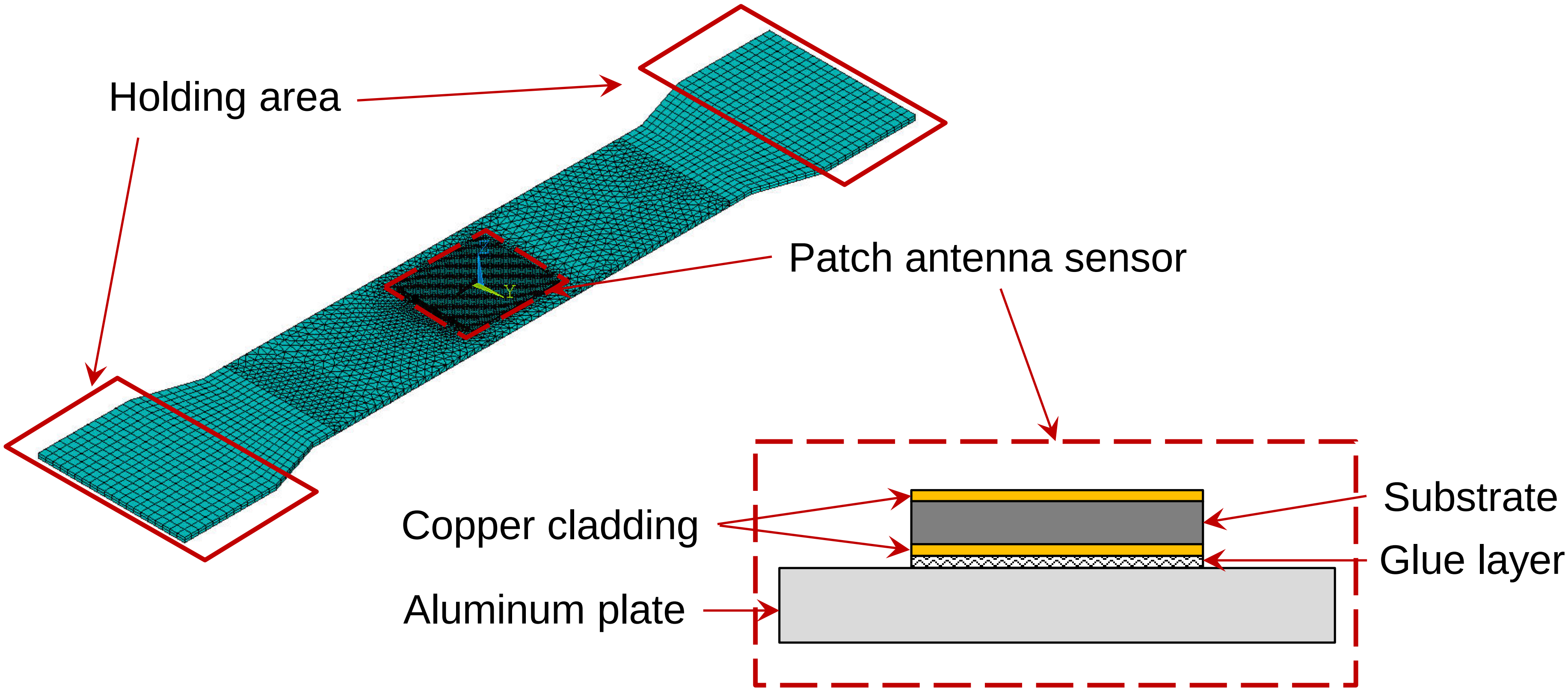
Five traditional strain gages (#7 ~ #11) are installed near the center of the aluminum tensile specimen.



Strain ratio between antenna sensor and aluminum specimen



Strain Transfer Ratio Simulation



- Nonlinear constitutive relationships are used for aluminum, copper, and substrate. (The constitutive relationships are measured by tensile tests.)

Model Updating for Adhesive

- Menegotto-Pinto model with parameters $(b, n, \varepsilon_0, \sigma_0)$ is adopted for nonlinear constitutive model of adhesive.
- Update the parameters $\mathbf{x} = [b, n, \varepsilon_0, \sigma_0]$ by minimizing the difference between experimental strain transfer ratios and simulated strain transfer ratios.

$$\min_{\mathbf{x}} \sum_{i=1}^{m} \left[T_{\mathrm{Exp}}(\varepsilon_i) - T_{\mathrm{Sim}}(\varepsilon_i, \mathbf{x})\right]^2$$

$$\mathrm{s.t.} \quad \mathbf{x}_{\mathrm{L}} \leq \mathbf{x} \leq \mathbf{x}_{\mathrm{U}}$$

where m : the number of strain steps

ε_i : strain level at *i*-th step

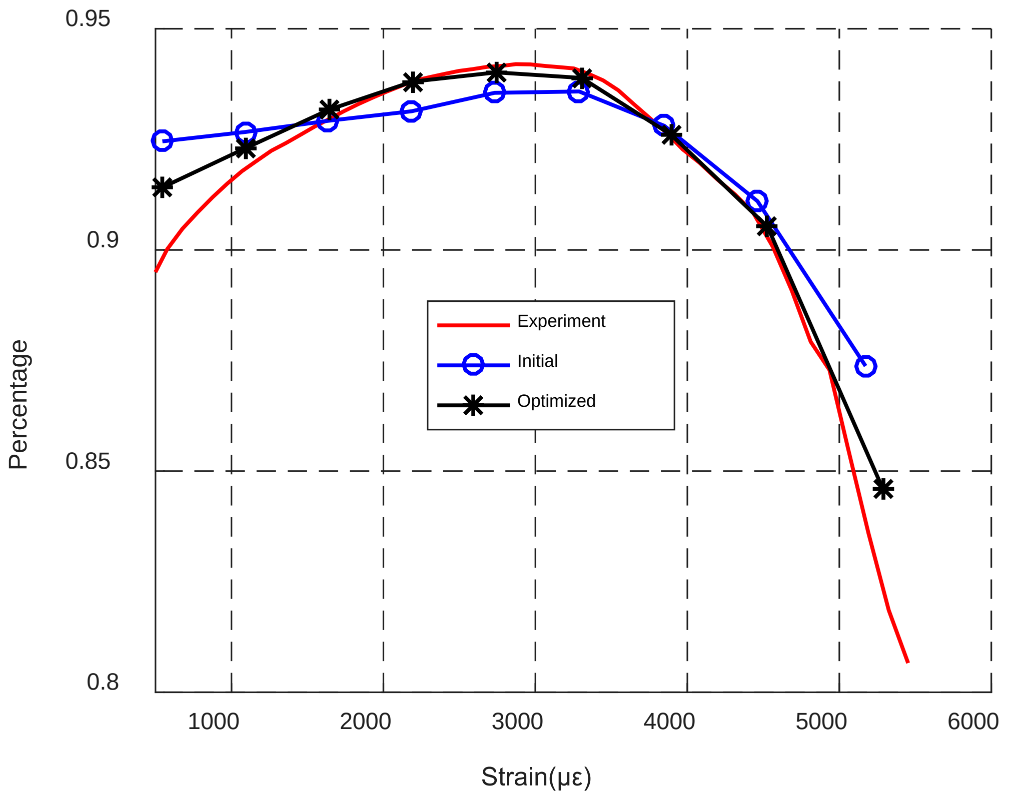
T_{Exp} : strain transfer ratio at ε_i from the experiment

T_{Sim} : strain transfer ratio at ε_i from the simulation

- The optimization problem is solved by Covariance Matrix Adaptation Evolution Strategy (CMA-ES) algorithm.

Hansen, N. (2006), "The CMA evolution strategy: a comparing review", *Towards a new evolutionary computation. Advances on estimation of distribution algorithms*, Springer, pp. 1769–1776.

Model Updating Result



After model updating on adhesive, the simulated strain transfer ratio is closer to the experimental strain transfer ratio.

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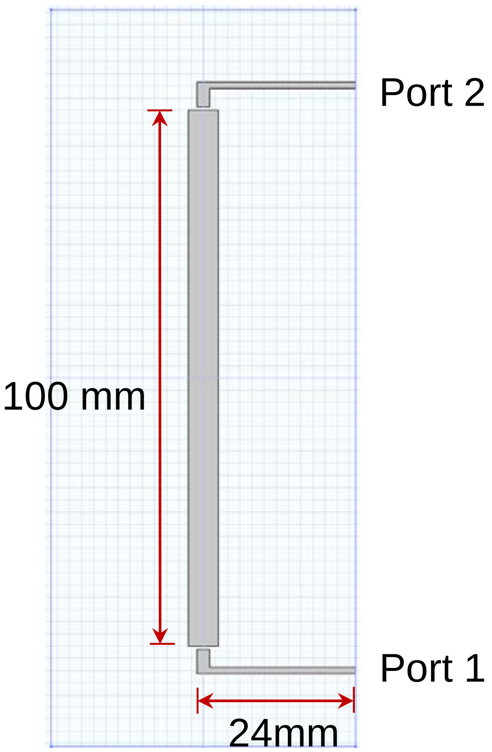
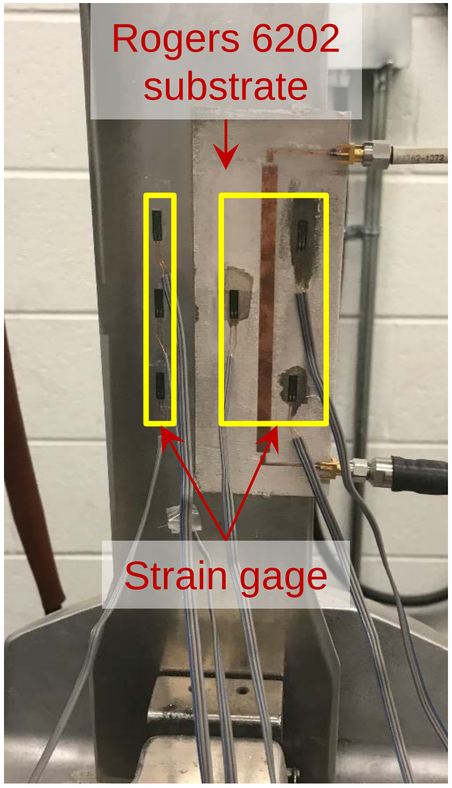
Transmission Line Test

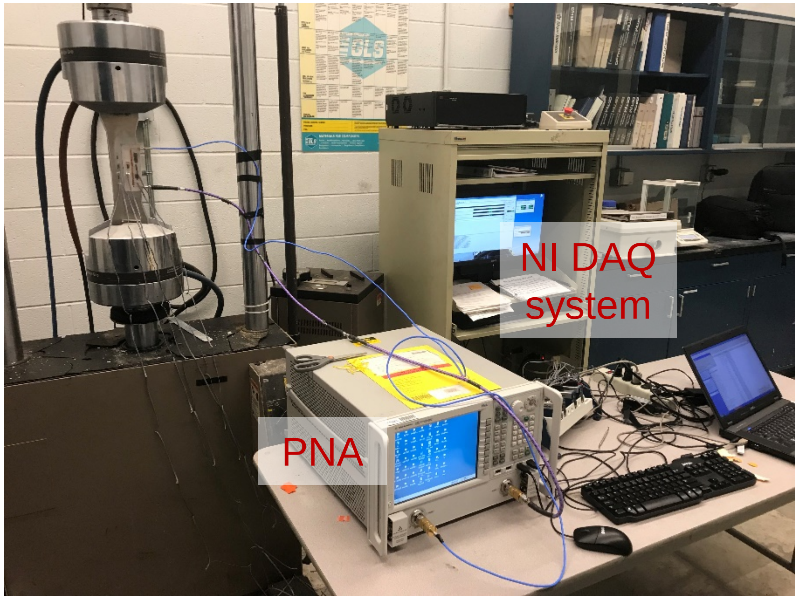
Measure $S_{21}(f) = \dfrac{V_2^{\text{out}}(f)}{V_1^{\text{in}}(f)}$ to update dielectric constant

Specimen

Experiment setup



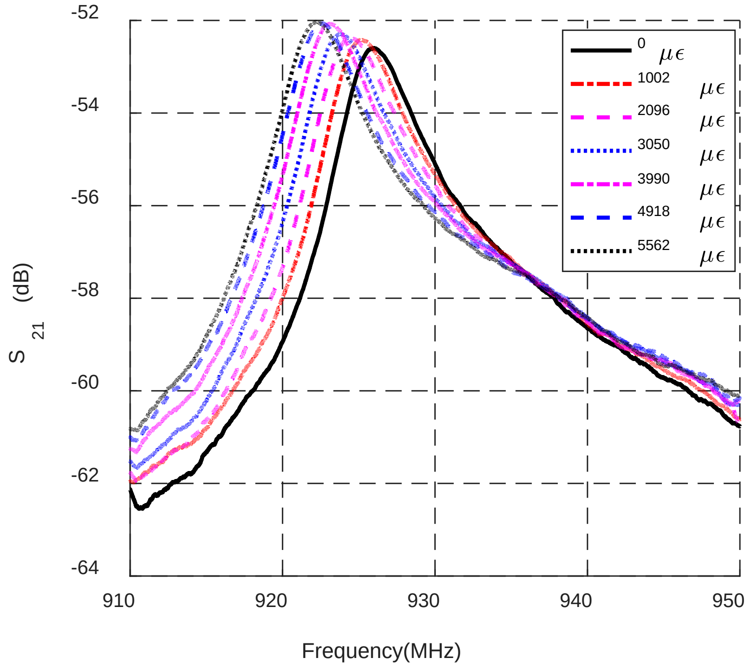




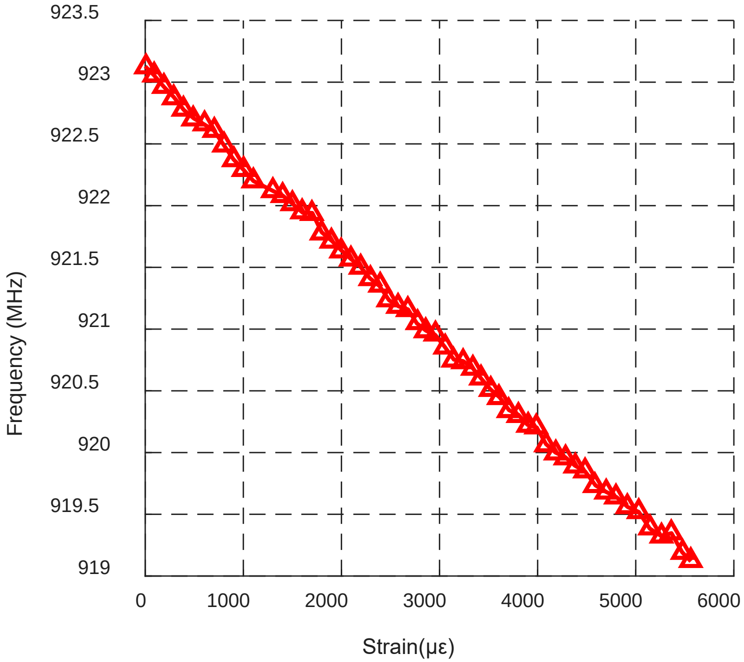
Transmission Line Test Results

- At each strain step, sweep through frequency band 910 ~ 950 MHz
- From S_{21} curve, resonance frequency is extracted

S_{21} curve



Resonance frequency at different strain level



Dielectric Constant Modelling

$$\beta = \beta_0 + \alpha_1 \varepsilon + \alpha_2 \varepsilon (1 - 2\upsilon)$$

where β_0 : dielectric constant value at zero strain

ε : strain level

υ : Poisson's ratio of the substrate

α_1 and α_2 : updating parameters

Update the parameters $\boldsymbol{\alpha} = [\alpha_1, \alpha_2]$ by minimizing the difference between experimental resonance frequencies and calculated resonance frequencies.

$$\min_{\boldsymbol{\alpha}} \sum_{i=1}^{m} \left[f_{\mathrm{Exp}}(\varepsilon_i) - f_{\mathrm{Cal}}(\varepsilon_i, \boldsymbol{\alpha}) \right]^2$$

$$\mathrm{s.t.} \quad \boldsymbol{\alpha}_{\mathrm{L}} \leq \boldsymbol{\alpha} \leq \boldsymbol{\alpha}_{\mathrm{U}}$$

where m : the number of strain steps

ε_i : strain level at *i*-th step

f_{Exp} : resonance frequency at ε_i from the experiment

f_{Cal} : resonance frequency at ε_i from the calculation

Updated Parameters For Dielectric Constant

$$\boldsymbol{\alpha}_0 = [\alpha_1, \alpha_2] = [-0.6, -1]$$

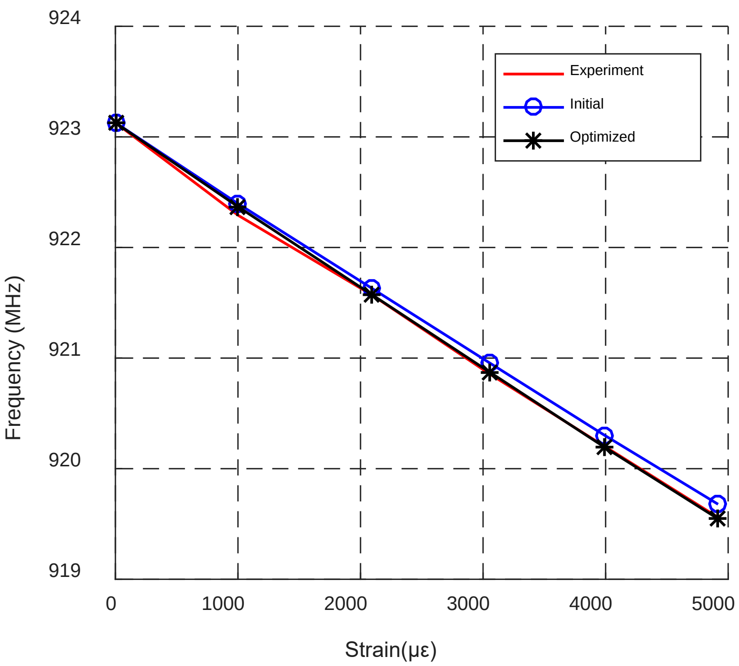
$$\boldsymbol{\alpha}_{\mathrm{L}} = [\alpha_1, \alpha_2] = [-1, -2.5]$$

$$\boldsymbol{\alpha}_{\mathrm{U}} = [\alpha_1, \alpha_2] = [-0.2, -0.5]$$

$$\boldsymbol{\alpha}^* = [\alpha_1, \alpha_2] = [-0.2913, -1.5748]$$

The strain effect on dielectric constant

$$\beta = \beta_0 - 0.2913\varepsilon - 1.5748\varepsilon(1 - 2\upsilon)$$



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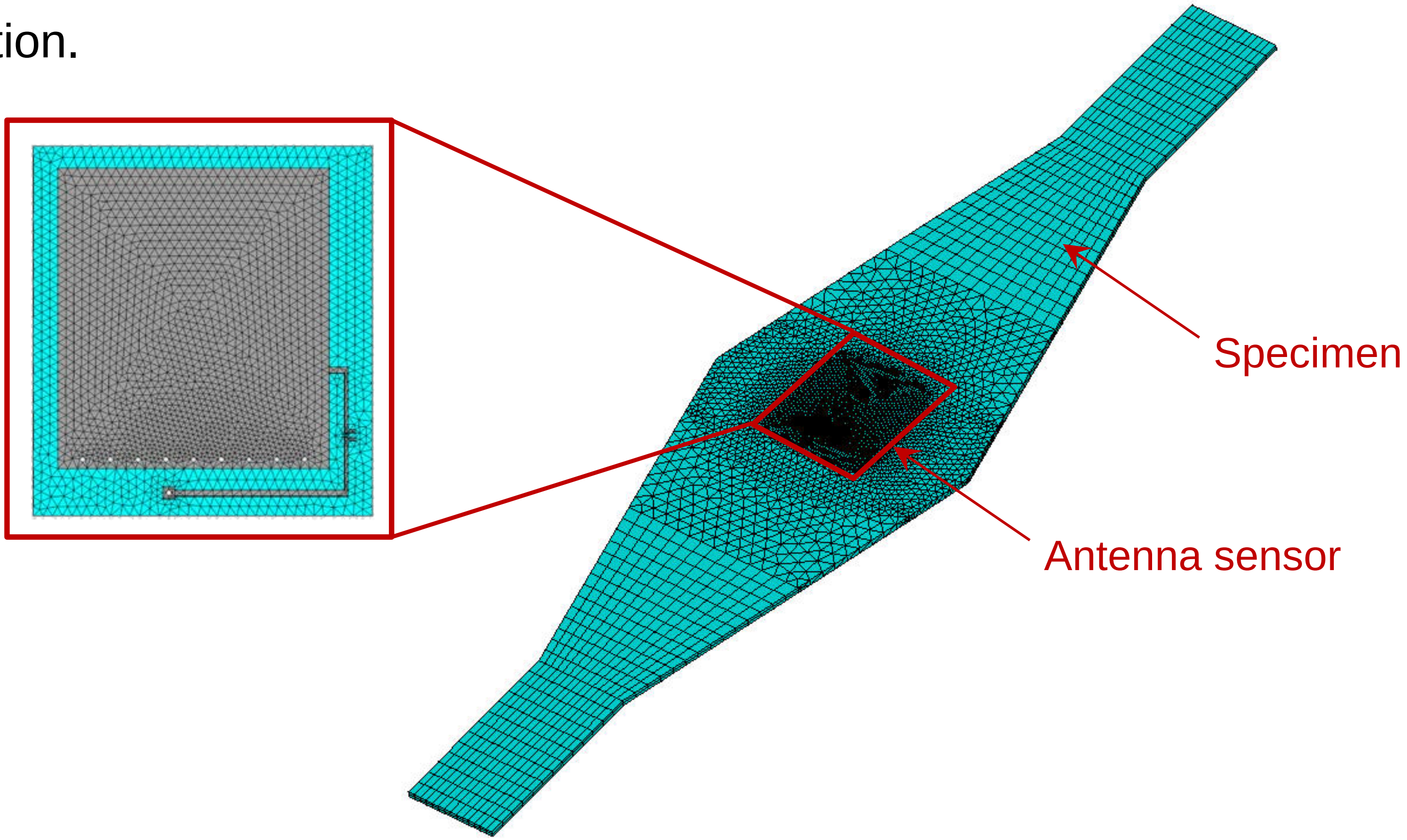
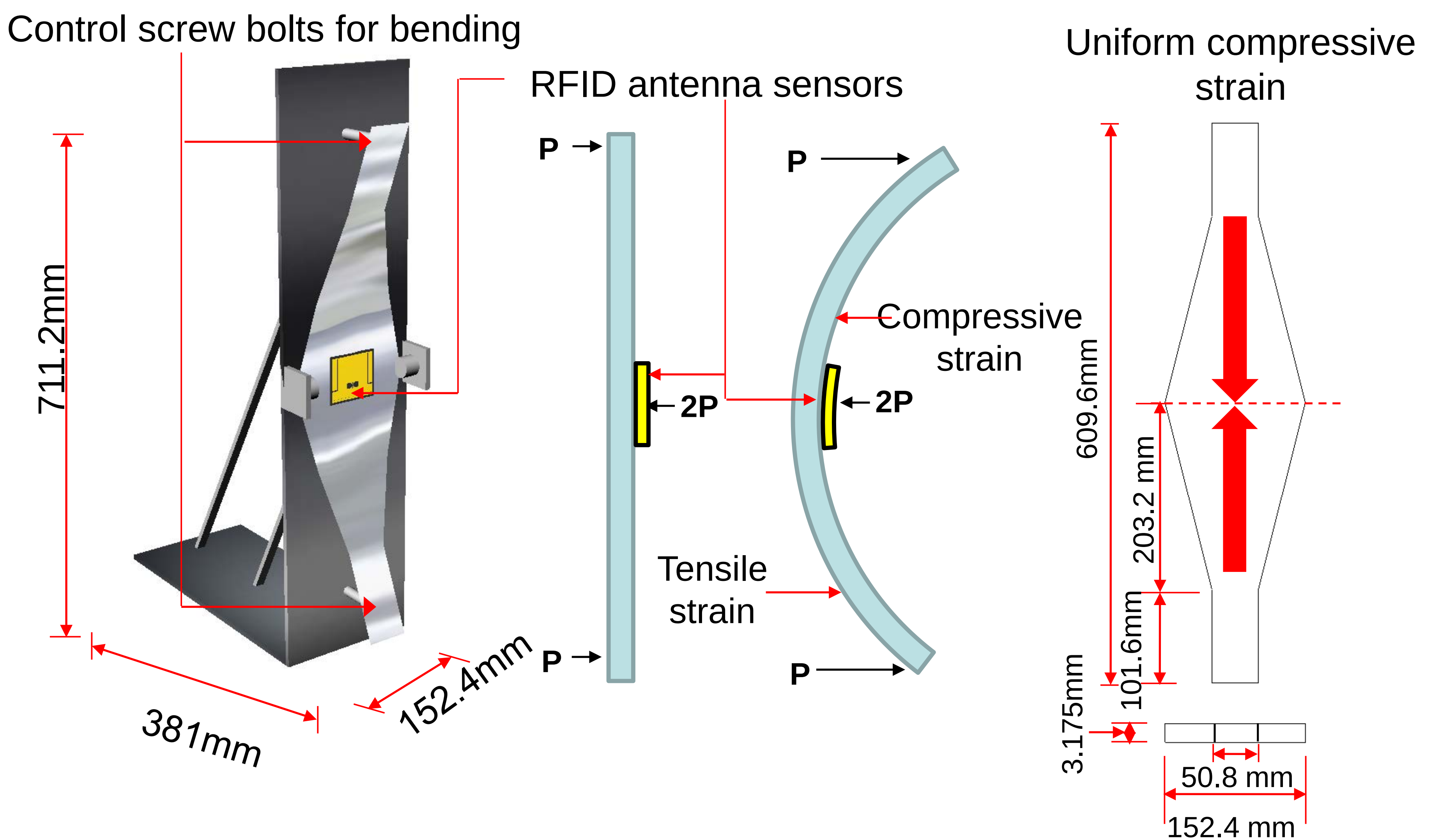
Multi-physics Simulation

- Mechanical simulations with linear constitutive properties and updated nonlinear constitutive properties are conducted.
- Dielectric constant change with strain is considered in the electromagnetic simulation.



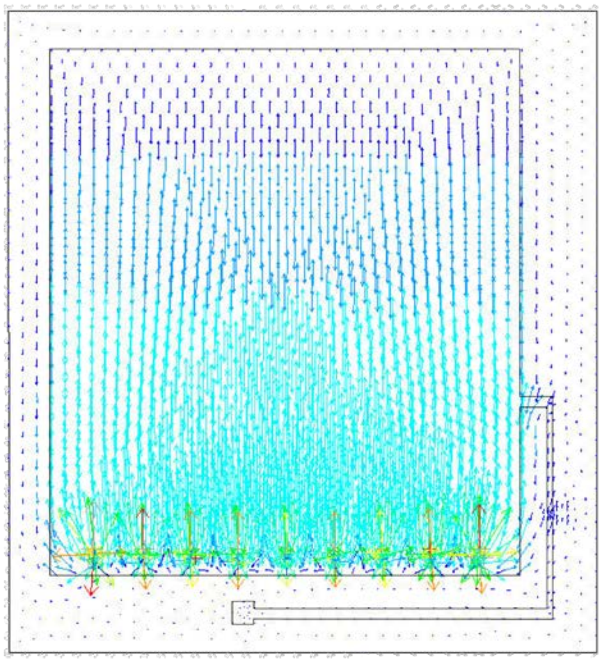
Finite element model

Three-point Bending Setup and Specimen Design

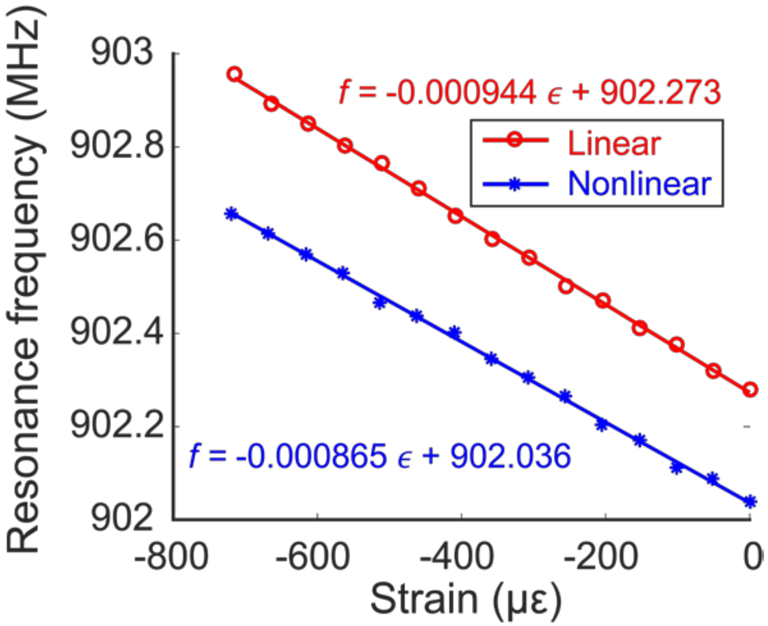


Simulation Results

- The relationship between average strain and resonance frequency is investigated.
- Strain sensitivity is calculated as –944 Hz/με using linear constitutive properties, and –865 Hz/με using nonlinear constitutive properties.



Surface Current



Resonance Frequency Change

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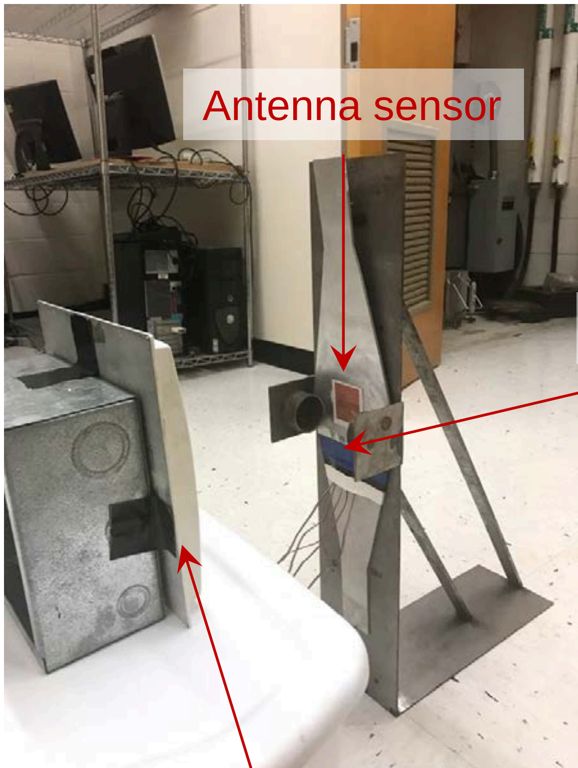
Compression Test

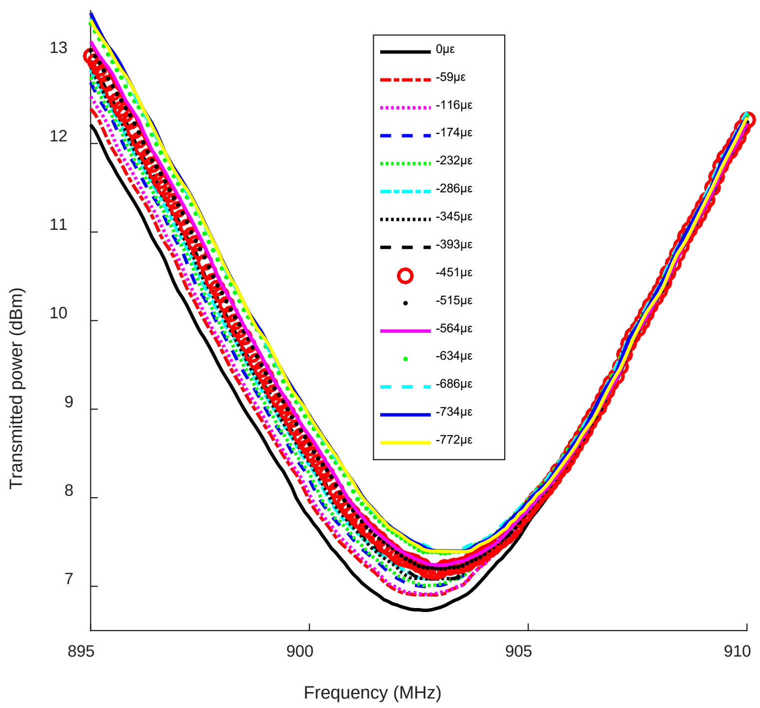
Experiment setup



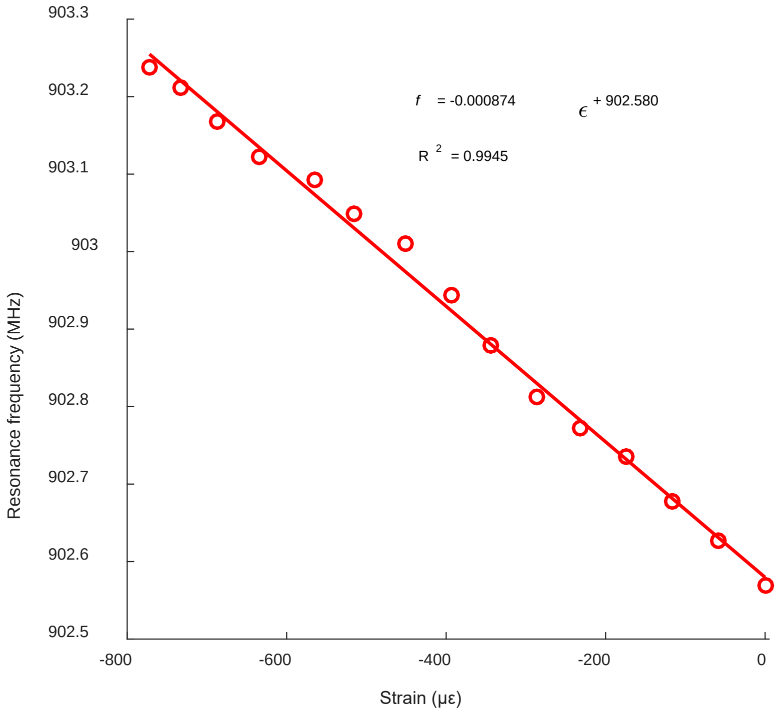
Compression Test Results

- At each strain level, sweep frequency band to get transmitted power curve.
- From transmitted power curve, the resonance frequency is extracted.

Transmitted power



Resonance frequency-strain curve

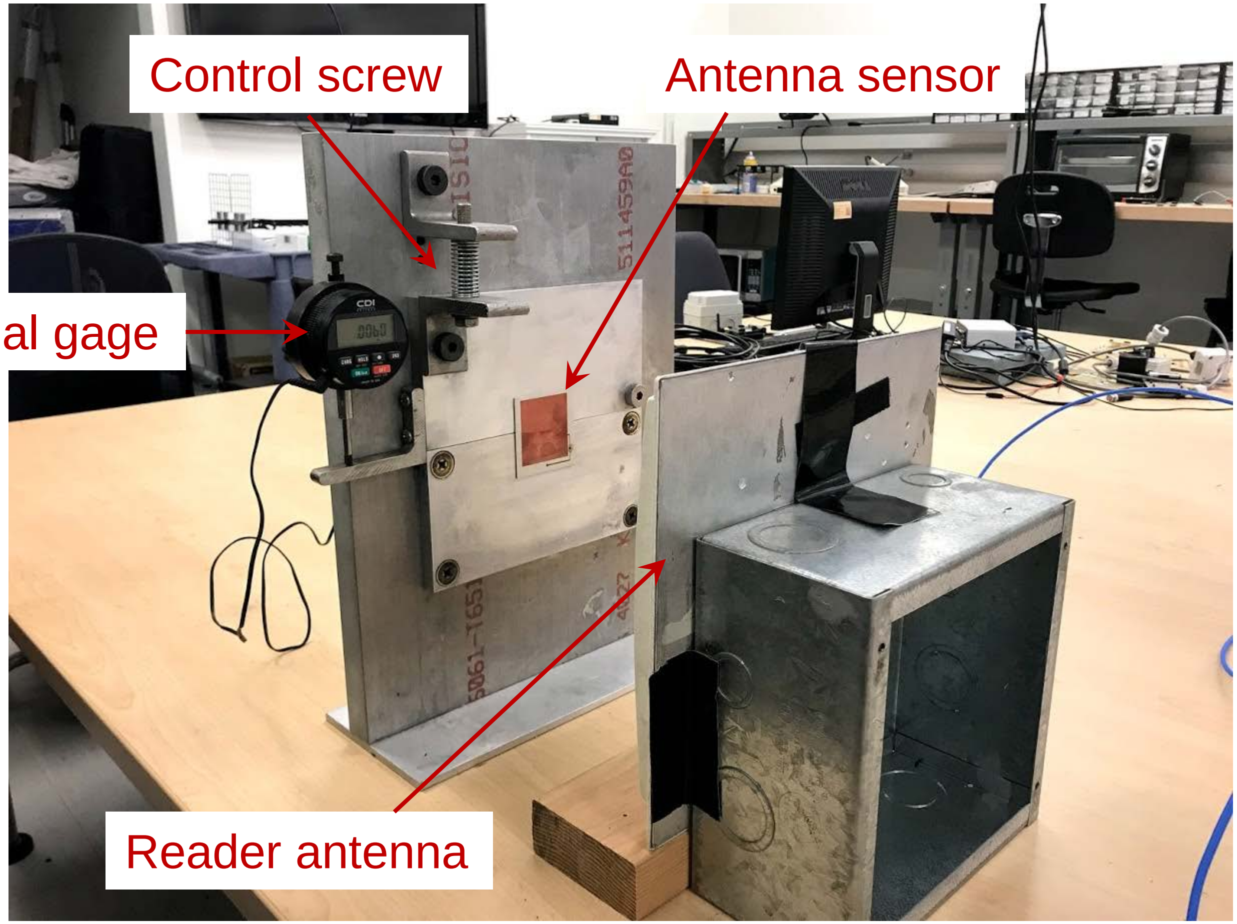


Outline

- Research Background & Motivation
- Thermal Stability Tests
  - Temperature Chamber Test
  - Day-long Outdoor Test
- Material Property Tests
  - Constitutive Relationship of Substrate
  - Constitutive Relationship of Glue
  - Dielectric Constant of Substrate
- Multi-Physics Simulation
- Validation Tests
  - Strain Sensing Test
  - Crack Sensing Test
- Conclusion

Crack Test

Experiment setup



Crack Propagation

2 mils

6 mils

10 mils

20 mils

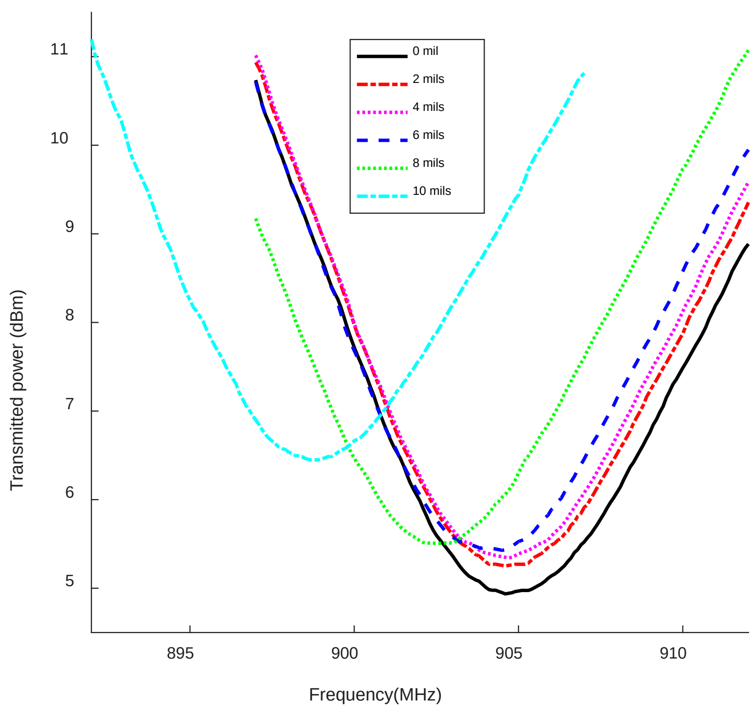
30 mils

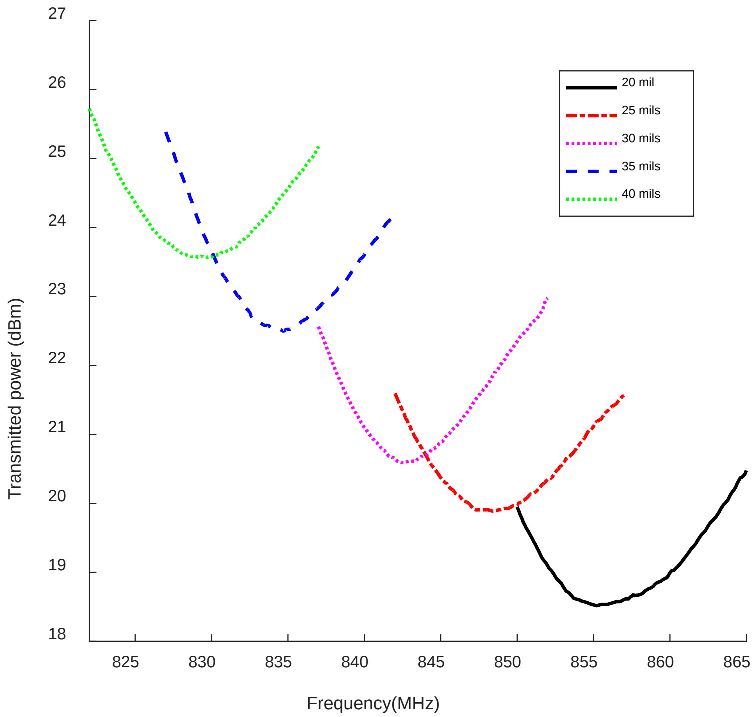
40 mils

Crack Test Results

At each crack level, sweep frequency band to get transmitted power curve.

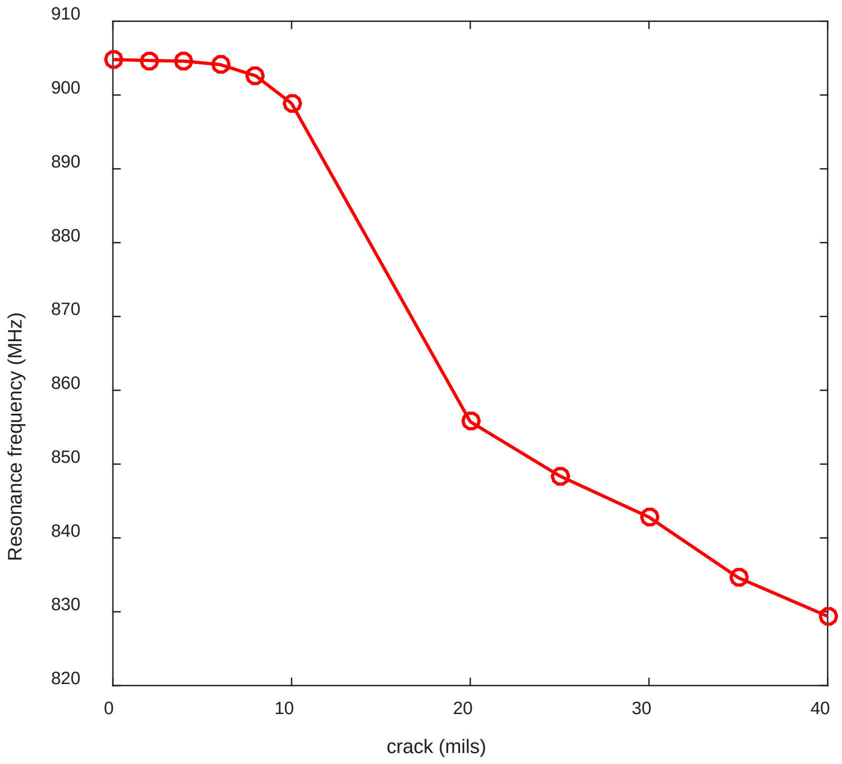
Transmitted power





Crack Rest Results

- From transmitted power curve, resonance frequency is extracted.
- The resonance frequency decreases as crack propagates along sensor's width direction.



Conclusions

1. The sensor with RT/duroid® 6202 substrate is shown to be more stable under outdoor environment disturbance compared with previous sensor with substrate material RT/duroid® 5880.

2. Multi-physics simulation can accurately model behaviors of the antenna sensor. Incorporating nonlinear constitutive properties in the model can improve the accuracy of the simulation results on strain sensitivity.

3. The antenna sensor is capable of estimating small strain changes on structures. The resonance frequency of the antenna sensor increases as the compression strain is applied.

4. The antenna sensor can monitor surface crack growth. As crack propagates, the resonance frequency of the antenna sensor reduces as expected.

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Thank You

Questions and Comments?